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Assessment of the renewable energies potential for intensive electricity production in the province of Jaén, southern Spain

J.A. Ruiz-Arias[a,c,*], J. Terrados[b], P. Pérez-Higueras[b], D. Pozo-Vázquez[c], G. Almonacid[a,b]

[a] Center of Advanced Studies in Energy and Environment, Campus Lagunillas, Building C6, University of Jaén, 23071 Jaén, Spain
[b] IDEA Research Group, Campus Lagunillas, University of Jaén, 23071 Jaén, Spain
[c] MATRAS Research Group, Campus Lagunillas, University of Jaén, 23071 Jaén, Spain

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ABSTRACT

The foreseen depletion of the traditional fossil fuels for the forthcoming decades is forcing us to seek for new sustainable and non-pollutant energy sources. Renewable energies rely on a decentralized scheme strongly dependent on the local resources availability. In this work, we tackle the study of the renewable energies potential for an intensive electricity production in the province of Jaén (southern Spain) which has a pronounced unbalance between its inner electricity production and consumption. The potential of biomass from olive pruning residues, solar photovoltaics (PV) and wind power has been analyzed using Geographical Information System tools, and a proposal for a massive implementation of renewable energies has been arisen. In particular, we propose the installation of 5 biomass facilities, totaling 98 MW of power capacity, with an estimated annual production of 763 GWh, 12 PV facilities, totaling 420 MW of power capacity, with an estimated annual production of 656 GWh and 506 MW of wind power capacity in a number of wind farms, with an estimated annual production of 825 GWh. Overall, this production frame would meet roughly a 75% of the electricity demands in the province and thus would mitigate the current unbalance.

Contents

1. Introduction

The energy world is facing a high uncertainty motivated by the current global economic crisis, the foreseen depletion of fossil resources and the climate change issue. Our fossil-fuels-based system is unsustainable and it is forcing us to seek for new non-pollutant energy sources that help us to mitigate the global warming to give response to the current and future energy requirements. To this respect it is important to have in mind that, due to the world's economic development, it is expected that the worldwide demand increases by 36% between 2008 and 2035 [1]. Additionally, both Europe and, particularly, Spain have an excessive dependence on outer fossil-fuels imports.

* Corresponding author at: Center of Advanced Studies in Energy and Environment, Campus Lagunillas, Building C6, University of Jaén, 23071 Jaén, Spain.
E-mail addresses: jararias@ujaen.es (J.A. Ruiz-Arias), jcepeda@ujaen.es (J. Terrados), pjperez@ujaen.es (P. Pérez-Higueras), dpozo@ujaen.es (D. Pozo-Vázquez), galmona@ujaen.es (G. Almonacid).

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The last World Energy Outlook of the International Energy Agency [1] proposes a new scenario to 2035 which takes into account the broad policy commitments and plans that have been recently announced by countries around the world. In this scenario, fossil fuels will remain the dominant energy source in 2035 supported primarily by the emergent countries, but the use of renewable energy triples between 2008 and 2035 and their share in electricity supply rises from 19% in 2008 to 32% in 2035. Also recently, Greenpeace has published a study [2,3] where sets out a roadmap to achieve a 68% of electricity production from renewables in Europe by 2030 and a 99.5% by 2050. According to this study, the 100% renewable electricity can be achieved through a large-scale integration of the European grid and an intelligent management of the local production based on the smart-grids concept. This idea is also held by the Desertec Foundation [4]. Therefore, promotion of renewable energies will play a major role in the next decades. Actually, the European Union (EU) objectives by 2020 set a binding target for 20% of the EU's total energy supply to come from renewables by 2020 and a firm target of cutting 20% of the EU's greenhouse gases emissions relative to 1990.

In this framework, several studies have proposed different socioeconomic scenarios and have analyzed the requirements to fulfill with the EU's commitments and their implications. Particularly, Gómez et al. [5] analyze the Spanish case based on nine different scenarios according to different economic and strategic criteria. Among its conclusions, the study highlights that the achievement of the 20% energy supply target implies that, approximately, 45% of the electricity should be of renewable origin by 2020 (assuming biofuels contribute with a 10% to the final energy consumption in the transport sector).

Contrarily to traditional generation of electricity, generation with renewables relies on a distributed scheme with a higher number of smaller production plants near the final consumers. This sort of distribution grid is specially suitable to be managed with smart power networks. Therefore, it is important to evaluate the potential for electricity production from sustainable and renewable sources at regional and local scales. In this work, we tackle the estimation of the real potential in the province of Jaén (southern Spain) for electricity production from biomass, solar PV and wind origin. This evaluation will serve as background for a subsequent study on the feasibility of a massive intervention in the local electrical grid with renewables. Currently, the province has a negative balance in production/consumption of electricity. Particularly, in 2008 the actual inner production was only 937 GWh, against a consumption of 3080 GWh [6]. This situation strongly contrasts with the rest of Spain, where the electricity production/consumption is well-balanced (296 TWh produced against 275 TWh consumed) [6]. This study intends to evaluate the renewables potential to revert this issue.

Biomass resources include almost any kind of organic residuals from vegetal or animal origin. Traditionally, they have been used for heating, but nowadays they are also considered as a source for electricity, bio-gas and bio-fuels production. Jaén is a rich-land in olive trees with more than 500,000 ha of olive crops. The olive oil industry generates an enormous amount of biomass by-products that are only partially used, mainly for heating, but still must be worth for electricity production. Sánchez et al. [7] estimated that, in average, only the olive pruning residuals amount up to 3 tons/ha per year. However, the current annual consumption of own biomass for energy production in Jaén is only about 600,000 tons: a 78% is used for heating (of which a half is consumed in the olive oil industry) and a 22% is used for electricity production [8]. In the past, some studies have explored the biomass potential from olive trees in the province [7,9,10]. However, none of them focused on its overall potential for electricity production. In this study, we specifically focus on the potential for electricity production using olive pruning residuals as fuel in biomass thermal plants.

In addition, the province also has considerable wind and solar potentials. Particularly, Jaén is one of the sunniest regions in Spain, with more than 1700 sunshine hours a year [8,11,12]. The electric production feasibility from wind energy in this area has been also demonstrated by the 15 MW power capacity wind farm that is commercially operating in the southern part of the province.

The distributed nature of renewable energies make them specially suitable to be studied using Geographical Information Systems (GIS), which have widely demonstrated their abilities in territory management problems. Particularly, many studies have been conducted worldwide using GIS tools for the evaluation of renewable energies potential [13–16]. In this work, GIS techniques have been a core tool to achieve meaningful results.

The work is organized as follows: Section 2 describes the study region and depicts its current energy frame. Section 3 presents the methodology approached for the estimation of biomass, PV and wind potentials and Section 4 presents the results for each renewable resource. Finally, main conclusions are presented in Section 5.

2. Site study

The province of Jaén is situated in the southern part of the Iberian Peninsula (Fig. 1). It occupies an extension of roughly 13,500 km^2 with a population totaling 669,000 inhabitants. Its territory is divided in two different topographic regions: the mountainous systems of the south-eastern and northern façades and the region in between, a flat land which houses the Upper Guadalquivir river basin. The highest peak is the Mágina Peak, in the southern façade, with 2167 m above sea level. The mean altitude in the river basin is around 300 m above sea level. The economy of the region is principally based on the olive oil industry. Actually, the olive oil production in Jaén is the 20% of the worldwide production and the 50% of the Spanish one.

The Spanish Ministry of Industry offers annual reports on electricity production and consumption in Spain [6]. According to the last available report (2008), the total electricity consumption in Jaén was 3080 GWh. By sectors, the domestic consumption was the most important (36%), followed by the industry (28%), services (13%) and the public sector (10%). Table 1 shows the structure for electricity production in the province, which is strongly supported by thermal plants. It mainly consists of cogeneration plants with a gas turbine that uses the heat to dry the olive-pomace sludge resultant after the olive oil grinding process. Currently, only two of the thermal plants of the province use biomass as fuel. Particularly, one of them (with 16 MW installed power capacity) uses direct combustion of the dry olive-pomace sludge produced in the neighboring cogeneration plants. The another one (4.3 MW installed power capacity) burns woody residuals from olive trees and ancillary industries. They together produced around 110 GWh in 2009. There are not combined cycles or fuel, coal or nuclear plants. Among

Table 1
Installed power (MW) and annual electricity production (GWh) in the province of Jaén in the last years [6]. The wind production in 2005 is included within the hydraulic production.

	2005		2006		2007		2008	
	MW	GWh	MW	GWh	MW	GWh	MW	GWh
Hydraulic	196	187	181	121	183	86	183	88
Wind	–	–	15	25	15	25	15	26
Photovoltaic	–	–	2	1	8	9	66	41
Thermal	110	426	110	422	101	486	151	782
Total	306	613	308	569	307	606	415	937

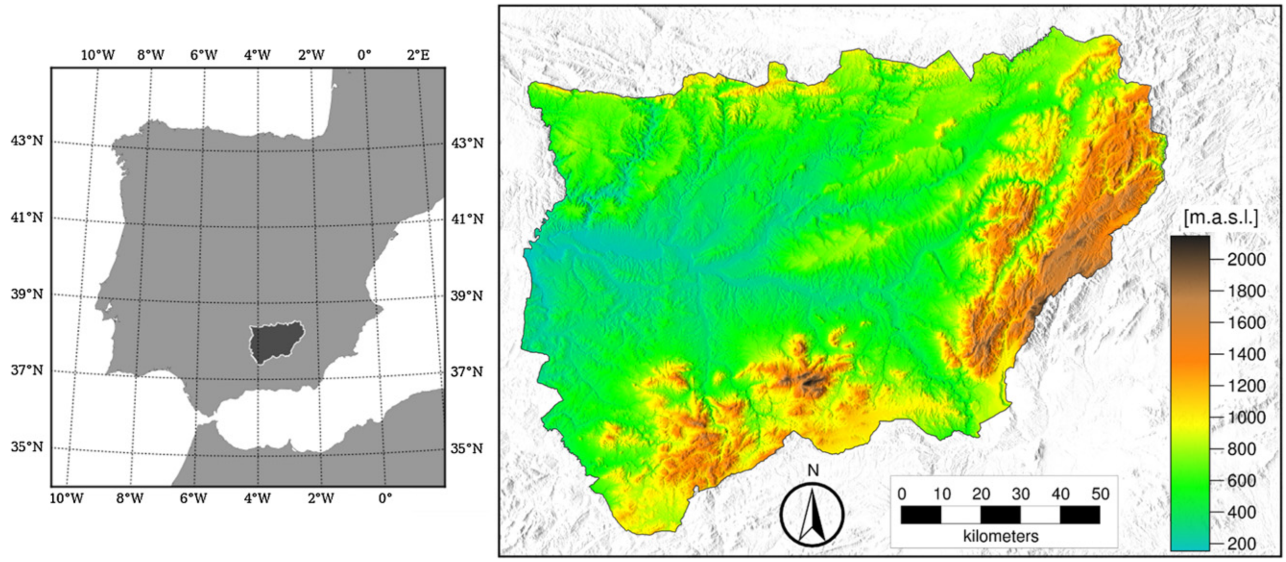

Fig. 1. Geographical location and topography (meters above mean sea level) of the province of Jaén.

the hydraulic facilities, approximately a 25% of the power production comes from small plants (below 10 MW). This distinction is important because only these plants are considered to have renewable origin in the current Spanish tariff system. Wind and solar photovoltaic only amount to around a 20% of the installed power and they contribute with a 7% to the total production. Photovoltaic installed power capacity consists of around 660 small installations (only some of them in the order of MW) and the wind installed power capacity corresponds to a wind farm in the southern part of the region. With this structure, around a 20% of the produced electricity is from renewable origin. Overall, the inner electrical system only supports a 32% of the demand and two thirds of the total consumption must be imported.

3. Methodology

The availability of renewable resources has been independently evaluated using a specific approach for each energy source. Following, the results have been analyzed using GIS tools. Particularly, digital models of the geographical distribution of the energy potentials were created considering restrictive criteria as topographic features or soil type and use. From these maps, an evaluation of the potential for electricity production with renewables was carried out.

3.1. Biomass potential from olive pruning residuals

In the last years, various studies have been conducted at regional scale aiming an evaluation of the volume of pruning residuals originated in the olive growing [9,10,17]. The biomass potential per hectare is usually estimated using a crop-specific biomass pruning residual index (η) which relates the residual production to the crop production. Particularly, the η for olive trees depends on factors as the climatic region, the irrigation level or the farming techniques. These studies have defined an averaged residual index (Table 2) for irrigated and non-irrigated olive crops and flat or sloping surfaces, which has proved to be an important factor as well. Additionally, residuals treatment and collection with farm machinery gets difficult in terrains with pronounced slopes and makes unfeasible their exploitation. Consequently, we have excluded those land surfaces with a slope above 20%.

Table 2
Biomass residuals production index for olive crops in tons/ha per year.

Terrain slope	Dry crops	Irrigated crops
Less than 10%	1.6	1.7
Greater than 10%	1.4	1.6
Greater than 20%	–	–

On this premise, the technical volume of olive pruning residuals ($V_{r,o}$) can be calculated from the total growing surface S_i (in ha) as:

$$V_{r,o} = S_i \times \eta_{o,i}, \tag{1}$$

where i stands for irrigated, non-irrigated, flat or sloping lands and $\eta_{o,i}$ is the corresponding olive pruning residual index per hectare.

To estimate the total surface of olive farms, we have used the land cover and soil uses database of the Andalusian Environmental Office [18]. As it is a vectorial database, we previously rasterized the land use categories with the same grid spacing as the digital elevation model that we used for the terrain modeling, the Shuttle Radar Topographic Mission 90 m digital elevation data [19]. The land cover database distinguishes between irrigated and non-irrigated olive growing and the digital elevation database allow us to separate by terrain slope. Additionally, previous studies [9] have also point out that the collection of biomass from a distance longer than 50 km is not profitable. To find out the best number and spatial distribution of the biomass burning facilities, we have carried out a preliminary study considering these constraints.

Finally, in order to assess the technical potential for electricity production, we used the operating data accumulated in the biomass electrical generation facilities that are currently operating in Spain.

3.2. Photovoltaic potential

In order to evaluate the solar resource at ground level, we used the clear-sky solar radiation model of the European Solar Radiation Atlas [20–22]. It has been profusely employed in practical applications as the assessment of solar radiation maps from satellite imagery [23,24] or as background for the generation of solar radiation and PV databases from ground measurements [25–27] or numerical weather models data [28]. This model represents the atmospheric extinction processes according to the Linke turbidity coefficient (T_L), which is the number of Rayleigh atmospheres radiatively equivalent to the actual atmosphere. The Linke turbidity is a climatic and dimensionless parameter given usually in a monthly basis. We retrieved its monthly values from the SODA

Table 3
Main technical specifications for the tested turbines.

Wind turbine	Rotor diameter (m)	Tower height (m)	Rated power (kW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)
G80	80	78	2000	4	13	25
G87	87	87	2000	4	12	25

database [29,30] at 20 randomly selected places throughout the study region. Then, we constructed the 12 monthly maps of the study region by spatial interpolation of the retrieved values using regularized splines with tension [31,32] and a grid support of 90 m of grid spacing.

Next, we used these interpolated maps to assess the incoming daily solar irradiation on the PV panels plane (see below) at a spatial resolution of 90 m. In order to precisely register the influence of the daytime sun path the time step for the daily integration of the solar irradiance was set to 12 min. The calculations were repeated day by day and the daily sums averaged every month. In addition, the terrain shadowing effects were also considered [24,33].

Following Blaesser and Munro [34], the PV potential for electricity production was evaluated based on a traditional fixed PV system with panels inclined 30° over the horizontal and permanently oriented southward (this reference configuration is close to the optimal for the latitudes of the region) as

$$E_{PV} = P_{inst}\frac{G}{G_{STC}}P_R, \tag{2}$$

where E_{PV} is the recovered energy, P_{inst} the installed power, G the incoming solar irradiation on the plane of the PV panel, G_{STC} is the incident irradiance at standard conditions (1000 W/m^2) and P_R is the performance ratio, which accounts for the different system losses. It uses to range from 0.70 to 0.80. In this case, we have used a value of 0.75 based on our experience in the region [35–37]. Typically, installation of 1 MW$_p$ requires around 2 ha of terrain [38,39].

3.3. Wind potential

Wind is a highly fluctuating resource both in space and time. This makes very difficult its estimation over a wide region based exclusively on ground measurements. Usually, there are not enough measurement sites nor measurements at different altitudes above ground (typically, from 60 to 80 m). Overall, this approach is often prohibitive from the economic point of view. Therefore, nowadays, the use of numerical weather prediction models is a common practice. They are able to generate comprehensive long-term data bases at high spatio-temporal resolutions. They perform a spatial and temporal disaggregation based on physical laws (known as dynamical downscaling) over the previously assimilated datasets from worldwide measurements of the atmosphere. In this study, we have used the Weather Research and Forecasting (WRF) model [40], one of the most used models for regional weather studies. A simulation over the southern half of the Iberian Peninsula, thus avoiding domain boundary effects over our region, was conducted for the whole 2007. The output was saved every hour with a spatial resolution of 9 km. In the vertical, which is very important for wind assessment, the atmosphere was described based on 27 unevenly distributed layers. A higher density of layers was set near the surface in order to achieve a better description of the turbulent transport processes that occur in these regions, which give rise to a high variability of the wind profile near the ground. Since most of the current windmills put their turbines at, roughly, 80 m above ground surface, the wind speed output from WRF was interpolated at this vertical level. Afterwards, a refinement of the maps was carried out by spatial interpolation using regularized splines with tension up to a grid spacing of 1 km.

The evaluation of the wind potential for electricity production was based on the power curves of two commercial turbines developed by Gamesa Corporation [41] (see Table 3). Given the power curve, $P(v)$, of the wind turbine, the produced energy, E_W, can be easily calculated from the local wind speed distribution, $\Phi(v)$, as

$$E_W = \int_{v_s}^{v_c} \Phi(v)P(v)dv, \tag{3}$$

where v_s is the cut-in wind speed, at which the turbine starts up to work, and v_c, the cut-out wind speed, is the speed above which it is locked for safety. The power curves of the turbines were modelized as [42]:

$$P(v) = \begin{cases} 0 & , v < v_s \\ P_R\dfrac{v^3 - v_s^3}{v_R^3 - v_s^3} & , v_s \leqslant v < v_R \\ P_R & , v_R \leqslant v < v_c \\ 0 & , v \geqslant v_c \end{cases} \tag{4}$$

where P_R is the rated (or maximum) power of the turbine and v_R is the speed at which the turbine reaches it. All these parameters for the tested turbines are provided in Table 3.

Usually, the performance and suitability of a turbine in a given site is measured with the number of (equivalent) hours, H_e, that the wind turbine must work at its rated power in order to produce the actual energy produced along a natural year. It is calculated as E_W/P_n:

4. Results

4.1. Biomass potential for electricity production

According to the land cover and soil uses database of the Andalusian Environmental Office, the total extension of olive crops in the province amounts to 572,358 ha and up to 491,031 ha of them (Fig. 2a) correspond to useful terrains for their exploitation (terrain slope below 20%). Almost a 10% are irrigated crops. Fig. 2b shows the spatial distribution of the olive pruning residuals, totalizing 755,657 tons per year. These figures have been obtained according to the values shown in Table 2 for the olive residual index.

In order to assess the potential for electricity production we analyzed the actual and expected consumption/production balances of some biomass thermal plants already operating and planned in Spain [e.g., 9,43]. In the last years we observed a tendency to build plants of either 16 MW or 25 MW of installed power capacity. Consequently, our study has been based on this sort of plants. Particularly, Table 4 summarizes the main figures for four 16 MW and two 25 MW plants of installed power capacity that operate in Spain and have been used as reference in this study. The yearly production rate is very similar for both 1.07 MWh and 1.12 MWh per ton of residuals, respectively. Overall, using the mean value for the six analyzed plants, the total production using all the available biomass residuals would be around 820 GWh a year. This production would require to install 110 MW of power capacity.

The distribution of the installed power over a number of plants requires a conscientious study considering aspects as the distance to the main transportation network, the electricity distribution network, urban areas and, most importantly, biomass availability and economic or political issues. However, we have carried out

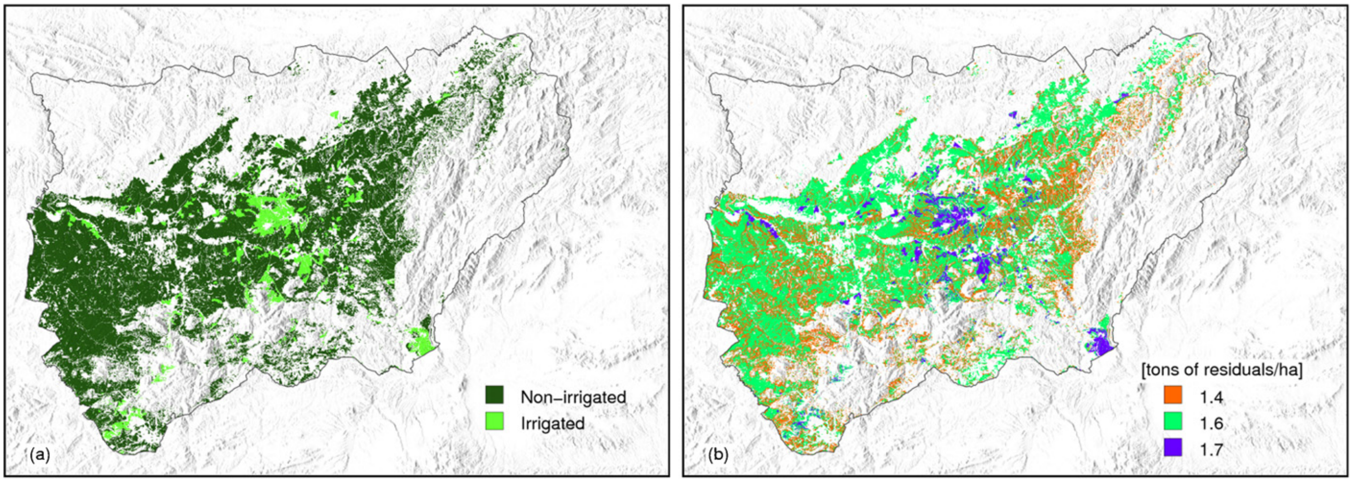

Fig. 2. (a) Geographical distribution of exploitable olive crops (terrain slope smaller than 20%) and (b) olive pruning residuals volume in the study region.

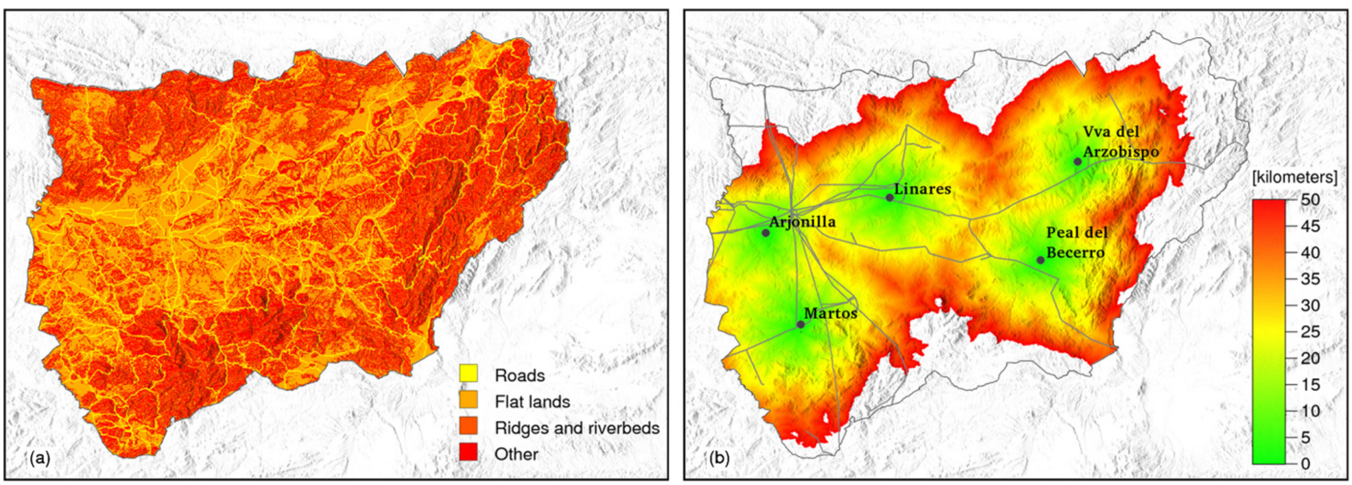

Fig. 3. (a) Cost surface of moving between adjacent cells. Roads have the lowest cost, followed by flat lands, ridges and riverbeds and other areas. (b) Location and distance to the biomass plants in kilometers according to the cost surface (a). The main electricity distribution network is also shown.

a preliminary study considering the fact that collecting biomass residuals from a distance longer than 50 km away the biomass production plant is not profitable. In order to calculate a real distance between two points taken into account that often the access to crops is not easy and requires secondary rural pathways, we have constructed a map showing the cost of moving between any two points. Fig. 3a shows the resultant cost surface in which roads and flat lands have the least cost. In rugged terrains, we assumed that rural pathways use natural avenues as ridges between consecutive hills and riverbeds. Therefore, we assigned a lower cost to the transition between cells that follow these paths, which have been modelized as the areas with an absolute terrain curvature (the slope derivative) above the percentile 75. The rest of cells were assigned with the highest cost value.

Once the cost surface was built, we tested different plants distribution scenarios trying also to minimize the distance of the plants to the transportation and electricity distribution networks. The best scenario resulted to be the installation of two plants of 25 MW of power capacity and three plants of 16 MW of power capacity. This particular distribution has been also based on the results reported by Lara-Chaves [17]. Fig. 3b shows the proposed location of the plants and the area of influence according to the

Table 4
Consumption and production rates of the biomass thermal plants used as reference in this study. The consumption rate per hour has been calculated assuming an annual operation cycle of 7500 h.

	Installed power (MW)	Consumption		Annual production rate (MWh/ton)
		(tons/year)	(tons/h)	
Linares	16	124,770	13.8	1.16
Vva. del Arzobispo	16	103,236	16.6	0.96
Burgos	16	105,000	14.0	1.14
Soria	16	120,000	16.0	1.00
León	25	175,000	23.3	1.07
Navarra	25	160,000	21.3	1.17

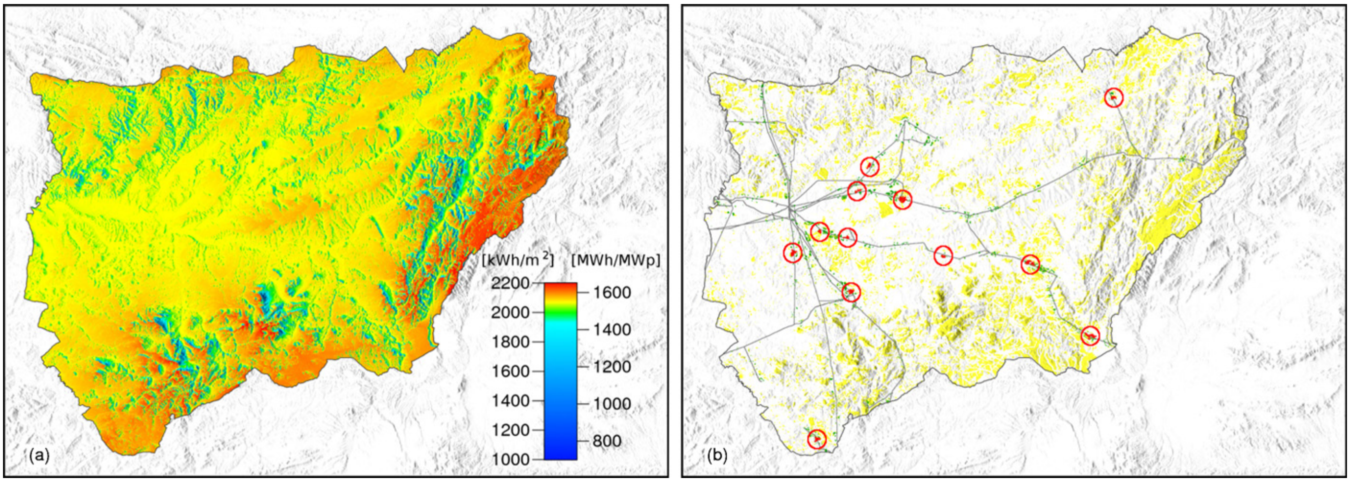

Fig. 4. (a) Spatial distribution of the yearly PV potential in a plane tilted 30° over the horizontal surface and southward-oriented. (b) Useful areas for PV exploitation (yellow patches) and proposed location (red patches) for 35 MW installed power capacity facilities. Green areas are useful regions near the electrical grid but with an extension smaller than 70 ha. The main electricity distribution network is also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Table 5
Installed power, available biomass and electricity production of the proposed biomass power facilities. The number of operating hours has been calculated based on the data shown in Table 4.

Plant	Installed power (MW)	Available biomass (tons/year)	Operating hours	Production (GWh/year)
Vva. del Arzobispo	16	114,239	7640	122
Peal del Becerro	16	117,384	7850	126
Linares	25	180,697	7734	193
Arjonilla	16	113,552	7594	122
Martos	25	186,494	7982	200
Total	98	712,366		763

cost surface. This distribution includes the 94% of the estimated production of biomass pruning residuals in the province. Table 5 shows the consumption and production figures of the plants. Overall, the annual total consumption is 712,366 tons of residuals which would generate 763 GWh (a 25% of the total annual consumption in the region and a 93% of the total biomass potential from olive pruning residuals).

4.2. PV potential for electricity production

As the ESRA model does not account for cloudiness, we have previously analyzed the relevance of this simplification by comparing the model estimates against a five years-length dataset of global solar radiation measurements in the roof of the Politechnic School of the University of Jaén. The measurements were taken in a 10 min basis on a horizontal surface, so a previous treatment was required to cast them over the same tilted plane as the PV panels. Following, they were integrated to a daily basis and then monthly averaged. Comparison of the observed and estimated data revealed a seasonal dependence. Particularly, in spring and fall seasons, the ESRA model error was very small (below 0.4 kWh/m^2). In summer, when the highest PV potential occurs, the differences increase up to 0.7 kWh/m^2, only a 9% of the daily total irradiation. However, in winter the error grows up to 1.2 kWh/m^2, a 40% of the total irradiation. This is presumably caused because the higher cloudiness in these months prevents an accurate estimation of the Linke turbidity coefficient. Nevertheless, for the whole year the total error of the estimates only represents a 7% of the total solar irradiation (0.5 kWh/m^2).

As regards to the spatial variability of the PV potential, mainly caused by topographic effects, Fig. 4a shows the spatial distribution of the yearly PV potential in a plane tilted 30° over the horizontal surface and southward-oriented. The minimum and maximum values are, respectively, 668 MWh and 1666 MWh per installed MW$_p$. However, 99% of the data range from 1325 MWh to 1666 MWh per installed MW$_p$. The mean value is 1550 MWh/MW$_p$. According to Eq. (2), the theoretical PV potential in the whole province amounts to approximately 1×10^6 GWh, more than 300 times higher than the total electricity consumption in 2008.

In order to evaluate the available PV potential, all those areas where the installation of PV facilities is unfeasible must be unaccounted. Therefore, based on the land cover and soil use database of the Andalusian Environmental Office the next areas were excluded:

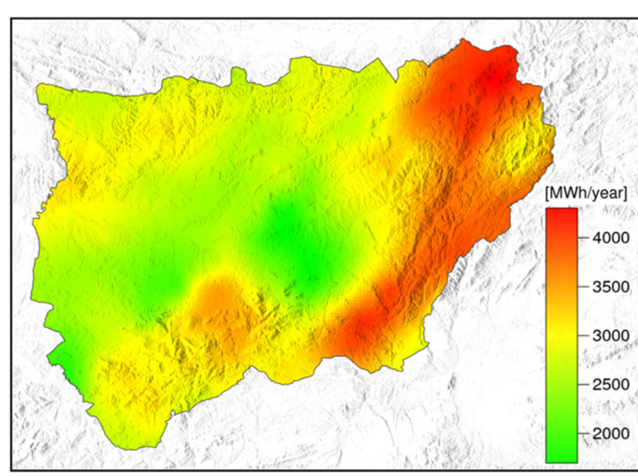

Fig. 5. Yearly production with a G87 wind turbine of 2 MW of power capacity throughout the region.

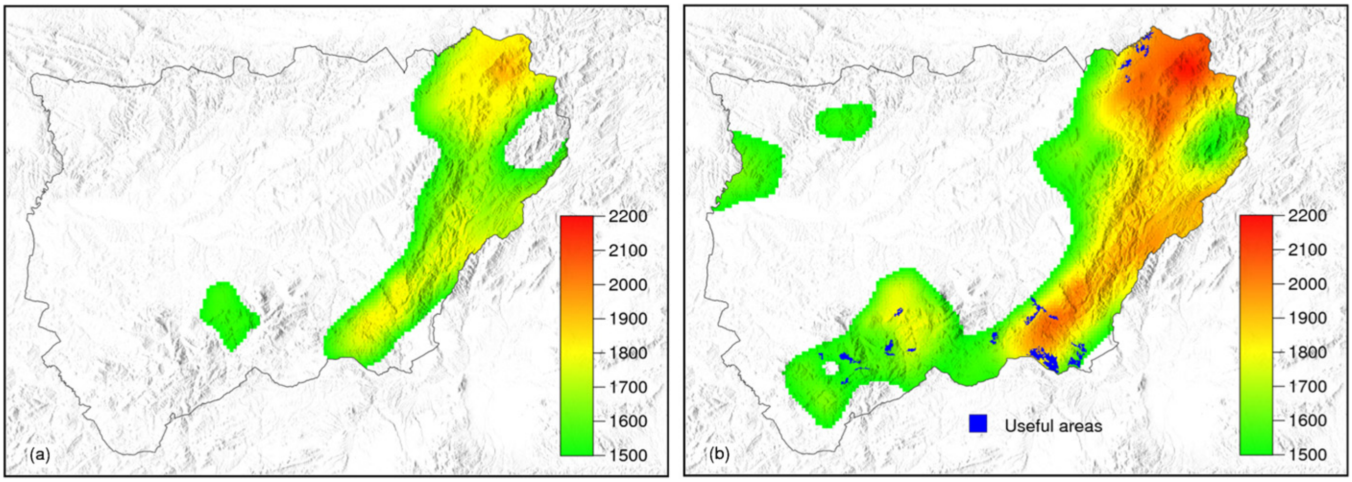

Fig. 6. Regions with more than 1500 equiv. h for both (a) the G80 turbine and (b) the G87 turbines. Blue patches are the suitable areas for the installation of wind farms. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

urban, industrial, leisure and commercial areas, dumping sites and irrigated and protected lands. Likewise, we have excluded rivers and water reservoirs, enforcing a minimum distance to the PV facilities of 200 m, and roads and railways, setting a minimum distance of 100 m. Fig. 4b shows the final useful areas (colored patches) for PV exploitation. They sum a total of 227,318 ha which, assuming a rate of 2 ha per megawatt of photovoltaic installed power capacity, amount a yearly production of 176 TWh (60 times higher than the total electricity consumption in 2008).

However, to further reduce the useful areas, we restricted them to terrain surfaces with slopes below 10% and a shorter distance than 1 km away the electricity distribution network. The aim was to avoid additional costs due to the terrain complexity or the required supplementary distribution network from the PV plant to the main distribution network. Green and red patches in Fig. 4b shows the areas subject to these new constraints. They amount a total surface of 7622 ha that would produce 5934 GWh. Particularly, red patches outline those areas with a surface extension greater than 70 ha. They could house PV facilities of 35 MW of installed power capacity. Overall, up to 12 PV plants could be installed, totaling 420 MW of power capacity that would produce a yearly sum of 656 GWh, a 21% of the total yearly consumption in the region.

4.3. Wind potential for electricity production

The yearly mean wind speed at 80 m above ground ranges from 4 m/s in the Guadalquivir river basin up to 7.5 m/s in the southern and eastern facades. Fig. 5 shows the yearly energy that would be produced with a G87 turbine. It reaches more than 4000 MWh in the south and eastern facades while only produces 1600 MWh in the river basin. Also note the partial complementarity with the PV solar distribution.

In order to evaluate the theoretical energy production, the number of wind turbines that can be installed must be previously determined. As a practical rule, to reduce aerodynamical losses by wakes every turbine needs at least a free squared area with a side size of approximately seven times the diameter of the rotor. Therefore, it could be installed up to 430 turbines G80 that would produce 1.1×10^5 GWh, 35 times the yearly total consumption in the province. In the case of the G87, it could be installed up to 364 turbines, with a similar production. However, installation of wind turbines is only feasible in part of the region. Fig. 6 shows the number of equivalent hours for both (a) the G80 and (b) the G87 turbines in those areas with a number of equivalent hours greater than 1500, which has been considered as a lower feasibility threshold. Overall, the G87 performs a higher number of hours and ranges a wider area indicating its higher suitability for the wind regime in this region. Therefore, below, our calculations refer to the G87 turbine.

Besides the limitation to more than 1500 equiv. h, we have restricted the suitable areas to abandoned crop fields and bushes and grazing lands, excluding too, particularly, protected areas as the Natural Park of Sierra de Cazorla, Segura y las Villas and Sierra Mágina. Fig. 6b also shows the useful areas (blue patches) with a surface extension greater than 110 ha, which is roughly the required extension for three wind turbines. These regions could house up to 253 windmills (506 MW of installed power capacity) that would produce around 825 GWh, a 27% of the yearly total consumption.

5. Conclusions

Compared to Andalusia and the rest of Spain, the province of Jaén has a marked unbalance between its inner electricity production and consumption. Particularly, it only produces one third of its total electricity consumption. Nevertheless, Jaén has a promising potential to increase its production quota based solely on local renewable resources which, additionally, contribute to reduce pollutant emissions to the environment and to fulfill with the EU's commitments by 2020. On the one side, its industry is mainly based on the olive oil, being the major worldwide producer. This industry generates a huge amount of wastes that can be used as fuel in biomass power plants. On the other side, the province also counts with large solar and wind resources.

In this work, we have analyzed the potential for producing electricity from olive pruning residuals, photovoltaics and wind in the province of Jaén. We have proposed a preliminary number and distribution of production facilities based on geographical and territory criteria. Olive pruning residuals have demonstrated potential for an annual production of 820 GWh. With the 5 proposed biomass thermal plants, totaling 98 MW of installed power capacity, 93% of the pruning residual could be exploited from a distance shorter than 50 km away the plants. Thus 763 GWh, a 25% of the total yearly consumption in the province, would be produced every year.

The theoretical PV potential in the region using PV panels inclined 30° over the horizontal surface and southward-oriented is 300 times higher than the total electrical consumption. When we restricted the production to the useful areas (see Section 4.2) which, additionally, are situated less than 1 km away the main

electricity distribution network, have a terrain slope below 10% and a surface larger than 70 ha, 12 PV facilities of 35 MW of power capacity each one could be installed. They would produce 656 GWh every year, a 21% of the total consumption.

Wind energy has also proved to have a large potential for exploitation. Particularly, we have tested two commercial wind turbines and both yielded a theoretical potential 35 times higher than the total yearly consumption of electricity in the province. Considering only those regions with more than 1500 equiv. h for the best wind turbine and restricting the suitable areas to abandoned crop fields and bushes and grazing lands, up to 253 turbines could be installed, totaling 506 MW installed power capacity that would produce 825 GWh per year, a 27% of the total consumption in the province.

Overall, the installation of 98 MW of biomass plants power capacity, 420 MW of PV power capacity and 506 MW of wind power capacity would produce up to 2244 GWh every year. Particularly, the PV and wind farm facilities would only require a 0.8% of the total surface of the province, mostly in marginal or sterile areas. In addition, if we count with the 177 GWh that were produced in 2009 in the province from biomass, PV and wind, the total renewable production would be a 78% of the electricity consumption. This would remedy the current production/consumption unbalance in the study region.

Finally, it is also worth to note that still remain additional sources for PV and biomass exploitation. Particularly, in-roof PV installations have undergone a great boost in the last years in Spain. But also the olive oil industry produces huge amount of other residuals that can be used to produce electricity or bio-fuels. Furthermore, the intermittent production of PV and wind facilities caused by weather variability and its impact in the electrical grid can be reduced by an smart operation planning of the biomass thermal facilities.

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